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Sir: Enclosed for filing please find the following provisional patent application:
Title: A Method For Transforming a Digital Signal From the Time Domain to the Frequency Domain

Enclosed please also find the following papers:

Serial Number: ______

Filing Date September 29, 2003

- ☒ 13 pages Specification; 4 pages claims; 0 pages abstract
- ☒ 2 sheets of drawings
- ☐ Power of Attorney
- ☐ Assignment of the invention
- ☐ A Verified Statement Claiming Small Entity Status

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Niky Economy Syrengelas, Esq.

A Method for transforming a digital signal from the time domain to the frequency domain

Background of the Invention

Domain transformation, specifically Discrete cosine transforms (DCT), are widely used in modern signal processing industry. Recently, a 'relative' of the DCT, called integer DCT, has attracted a lot of research interests because of its important role in lossless coding applications. The term 'lossless' means that the decoder can generate an exact copy of the source signal from the encoded bit-stream.

The DCT is a real-valued block transform. Even if the input block consists of all integers, the output block of the DCT are made of real numbers. For convenience, the input block is referred as input vector and the output block as output vector. If a vector has all integer components, it is called an integer vector. In contrast to the DCT, the integer DCT generates an integer output vector from an integer input vector. For the same integer input vector, the integer output vector of integer DCT closely approximates the real output vector of DCT. Thus the integer DCT keeps all the good properties of the DCT in spectrum analysis.

An important property of the integer DCT is reversibility. Reversibility means that there exists an integer inverse DCT (IDCT) so that if the integer DCT generates output vector $\boldsymbol{y}$ from input vector $\boldsymbol{x}$, the integer IDCT can recover vector $\boldsymbol{x}$ from vector $\boldsymbol{y}$. Sometimes the integer DCT is also referred as the forward transform, and the integer IDCT as the backward or inverse transform.

A transform called integer modified discrete cosine transform (IntMDCT) is recently proposed and used in the ISO/IEC MPEG-4 audio compression. It is shown in [2] that the core of IntMDCT is an integer type-IV DCT (DCT-IV). This motivates us to search for

an efficient fast algorithm, specifically for the integer DCT-IV algorithm. There are four types of DCT, and the fourth type is of particular interest. Fast algorithms refer to those efficient methods to compute a transform.

To obtain a fast algorithm for integer DCT-IV, the direct approach is to modify existing DCT-IV fast algorithms. As an example, Wang gave a DCT-IV fast algorithm in [4]. This algorithm can be converted to an integer DCT-IV fast algorithm by factorizing each butterfly operation (Givens rotation) into three 'lifting steps'. A detailed explanation of this factorization method can be found in [2]. For this type of integer DCT-IV algorithms, the total rounding number is at level $N\log_2 N$, where N is the block size. Here, rounding means the operation to round a real number to its nearest integer. Due to roundings, there is a difference between the outputs of integer DCT-IV and DCT-IV under same inputs. This difference is referred as approximation error. Generally, this approximation error increases with the total rounding number of the integer algorithm. A good integer DCT-IV algorithm should use as less roundings as possible.

In this invention, a method for transforming a digital signal from the time domain to the frequency domain, in particular reversible integer transform like DCT IV is introduced. The total rounding number of the method according to the invention can be significantly reduced, for example in case of DCT IV to be as low as $1.5N$. As a result, the approximation error of the method according to the invention is far less than that of the directly converted integer transforms. The computational complexity of the proposed method is also very low.

Summary of the Invention

The invention relates to a method for transforming a digital signal from the time domain to the frequency domain. The method can be used for any types of digital signal, such as audio, image or video signals. The digital signal, which corresponds to a physical measured signal, may be generated by scanning at least a characteristic feature of a corresponding analog signal (for example, the luminance and chrominance values of a

video signal, the amplitude of an analog sound signal, or the analog sensing signal from a sensor). The digital signal comprises a plurality of data symbols. The data symbols of the digital signal are grouped into blocks, with each block having the same predefined number of data symbols based on the sampling rate of the corresponding analog signal.

The digital signal is transformed to the frequency domain by a transforming element based on a transformation function which is implemented within a transformation matrix. In this method according to the invention, the transforming element transforms the digital signal by processing two blocks of data symbols as input signals simultaneously to generate two corresponding blocks of transformed output signal. It should be noted that the block size of the input signals and the output signals are the same.

An example of a transformation matrix is:

$$\begin{bmatrix} & C_N^{IV} \\ C_N^{IV} & \end{bmatrix}$$

wherein C_N^{IV} is a matrix representing the transformation function. C_N^{IV} shall be referred as the transformation function matrix henceforth.

The transforming element includes a plurality of lifting stages. A first lifting stage receives the two sub-blocks as first and second input signals, respectively. The first input signal is processed in a transformation path in the first lifting stage which includes a domain transformer, a rounding unit and a summation unit. The domain transformer can be any type of non-integer (real value) transformation function. The transformed first input signal is summed with the second input signal and result in an output signal. The output signal and the first input signal of the first lifting stage are used as the first and second input signals for a second (or subsequent) lifting stage, resulting in an output signal by the second lifting stage. Similarly, the output signal and the first input signal of the second lifting stage are used as the first and second input signals for another subsequent lifting stage. Since the output signal and the first input signal from each stage

are received by the subsequent stage, these two signals shall be considered to be signals output from each of the lifting stages, although the second input signal of the subsequent stage is identical to the first input signal of the previous stage (i.e. not transformed).

The transforming element can be illustrated based on the model of a lifting ladder. The lifting ladder model has two side pieces, each for receiving one of the two blocks of data symbols. Two or more cascading lifting stages are provided between the two side pieces. Each lifting stage receives a signal at one end (input end), and outputs a signal at the other end (output end) via a summation unit. A domain transformer is arranged at the input end of the lifting stage, and a rounding unit is arranged at the output end, between the domain transformer and the summation unit. The lifting stages are arranged between the side pieces in an alternating manner, such that the output (or input) ends of adjacent lifting stages are connected to the different side pieces.

It should be noted that although the transforming element is described in the form of the lifting ladder model, it is only to illustrate the transformation paths of the transforming element. However, the invention shall not be limited to said ladder model.

Figure 1 shows a flow chart of an embodiment of the method according to the invention using three lifting stages. In Fig.1, x_1 and x_2 are first and second blocks of the digital signal, respectively. z is an intermediate signal, and y_1 and y_2 are output signals corresponding to the respective first and second block of the digital signal.

The method according to the invention can be used for transforming an input digital signal which represents integer values to an output signal which also represents integer values. In other words, a "same word-length" transformation is performed such that word-lengths of the input signal and the output signal are the same (for example, a 8-bit input data is transformed to a 8-bit output data). Since both the input and output signals have the same word-length, the transformation method according to the invention is reversible. The output signal may be transformed back to the original input signal by performing the transformation method according to the invention. Such a reversibility

property of the transformation according to the method of the invention can be used in lossless coding in which the output signal should be identical to the original input signal.

Due to this reversibility property, the invention shall also include the transforming of a digital signal from the frequency domain to the time domain using the transformation element as described earlier.

Such a same word-length (or integer) transformation of signals according to the invention can be used in many applications and systems such as MPEG audio, image and video compression, JPEG2000 or spectral analysers (for analyzing Infrared, Ultra-violet or Nuclear Magnetic Radiation signals). It can also be easily implemented in hardware systems such as in a fixed-point Digital Signal Processor (DSP), without having to consider factors such as overflow in the case of a real-value signal transformation.

The transformation function used for the transformation of the digital signal according to the invention can be any kind of transformation function which can be represented as an Involutory Matrix. An Involutory Matrix is a matrix when multiplied with itself forms an Identity Matrix.

Let T be a matrix. T is an Involutory Matrix if it satisfies the following equation:

$$T \bullet T = I_N,$$

$$\text{where } I_N = \begin{bmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & \ddots & \\ & & & & 1 \end{bmatrix} \text{ is an Identity Matrix.}$$

Examples of transformation functions which can be represented as an Involutory Matrix includes, but not limited to, Discrete Cosine Transform (DCT) I, DCT IV, Discrete Sine

Transform (DST) I, DST IV, Discrete Fourier Transform (DFT) I, DFT IV, Discrete Wavelet Transform (DWT) I and Discrete Wavelet Transform IV. Therefore, these transformation functions can be used as the transformation function in the method according to the invention.

The domain transformers in the transforming element are implemented using the same transformation function that are used within the transformation matrix. However, the fast algorithms for implementing the transformation function for each of the domain transformers may be different. For example, when DCT IV is used as the transformation function for transforming the input digital signal, all the domain transformers should also be implemented using a DCT IV transformation function. However, various algorithms can be used to implement the DCT IV transformation function. Such algorithms include DCT II or FFT algorithms. Therefore, a different algorithm may be used in each of the domain transformers for implementing the DCT IV transformation functions. Alternatively, the same algorithm may be used in all the domain transformers.

As can be seen from the method according to the invention, all the data symbols in each block of the digital signal are provided to the transforming element as a data vector. In each lifting stage, the data vector is transformed in the domain transformer, and the transformed data vector is rounded subsequently to an integer vector (i.e. after the transformation in each lifting stage). In other words, rounding is performed in the method of the invention once on the data vector as a whole. This is in contrast to any method according to the state of the art, wherein the rounding process is performed within the transformation process for the individual element or data symbol in each block of the digital signal. Thus, the number of rounding operations in the method according to the invention is greatly reduced. Due to the reduced number of rounding operations, the method according to the invention does not require large computation time and computer resource.

The transformation matrix, which comprises the transformation function as sub-matrices, can be further decomposed into a plurality of lifting matrices. Each of the lifting matrices

corresponds to each lifting stage of the transformation element. A mathematical example illustrating this implementation will be shown later..

Each lifting matrix comprises four sub-matrices, with two permutation matrices as two of the sub-matrices in one diagonal, and a zero and a transformation function matrix as the other two of the sub-matrices in the other diagonal. A permutation matrix is a matrix which changes the position of the elements in another matrix. An example of a lifting matrix is:

$$\begin{bmatrix} P2_N & 0 \\ C_N^{IV} & P1_N \end{bmatrix}$$

wherein C_N^{IV} is the transformation function matrix, and $P1_N$ and $P2_N$ are permutation matrices. The permutation matrices may also be identical. The permutation matrices may also be arranged in the lifting matrix as $\begin{bmatrix} 0 & P1_N \\ P2_N & C_N^{IV} \end{bmatrix}$.

Also, Identity Matrix is commonly used as a form of permutation matrix. An Identity Matrix is a matrix shown in the following:

$$I_N = \begin{bmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & \ddots & \\ & & & & 1 \end{bmatrix}$$

The number of lifting matrices, and hence the number of lifting stages in the transformation element, is three, if the DCT-IV is the transformation function.

It should be noted that each of the elements in the lifting matrices is a matrix itself.

The invention not only relates to a method for transforming a digital signal from the time domain to the frequency domain (and vice versa), but also includes a computer program, a computer readable medium and a device for implementing the said method.

Example of the method according to the invention based on an Integer-type DCT IV as the transformation function.

An example of the method according to the invention is illustrated using the DCT-IV transformation function. The DCT-IV of a N-point real input sequence $x(n)$ is defined as follows [3]:

$$y(m) = \sqrt{\frac{2}{N}} \sum_{n=0}^{N-1} x(n) \cos\left(\frac{(m+1/2)(n+1/2)\pi}{N}\right) \quad m,n = 0,1,\cdots,N-1 \tag{1}$$

Let C_N^{IV} be the transformation matrix of DCT-IV, that is

$$C_N^{IV} = \sqrt{\frac{2}{N}} \left[\cos\left(\frac{(m+1/2)(n+1/2)\pi}{N}\right)\right]_{m,n=0,1,\cdots,N-1} \tag{2}$$

The following relation holds for the inverse DCT-IV matrix [3]:

$$\left(C_N^{IV}\right)^{-1} = C_N^{IV} \tag{3}$$

Let $\boldsymbol{x} = [x(n)]_{n=0,1,\cdots,N-1}$ and $\boldsymbol{y} = [y(m)]_{m=0,1,\cdots,N-1}$ be two $N \times 1$ column vectors, Equation (1) can be expressed as

$$\boldsymbol{y} = C_N^{IV} \boldsymbol{x} \tag{4}$$

Now, assume that there are two real, integer $N \times 1$ column vectors $\boldsymbol{x}_1, \boldsymbol{x}_2$. The column vectors $\boldsymbol{x}_1, \boldsymbol{x}_2$ correspond to the first and second blocks of the digital signal. The DCT-IV transforms of $\boldsymbol{x}_1, \boldsymbol{x}_2$ are $\boldsymbol{y}_1, \boldsymbol{y}_2$, respectively.

$$\boldsymbol{y}_1 = C_N^{IV} \boldsymbol{x}_1 \tag{5}$$

$$\boldsymbol{y}_2 = C_N^{IV} \boldsymbol{x}_2 \tag{6}$$

Combining (5) and (6):

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \boldsymbol{y}_2 \end{bmatrix} = \begin{bmatrix} C_N^{IV} & \\ & C_N^{IV} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \end{bmatrix} \tag{7}$$

Or, alternatively,

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \boldsymbol{y}_2 \end{bmatrix} = \begin{bmatrix} & C_N^{IV} \\ C_N^{IV} & \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_2 \\ \boldsymbol{x}_1 \end{bmatrix} \tag{8}$$

Let T_{2N} be the counter diagonal matrix of C_N^{IV} in (8), that is

$$T_{2N} = \begin{bmatrix} & C_N^{IV} \\ C_N^{IV} & \end{bmatrix} \tag{9}$$

Matrix T_{2N} can be factorized as follows:

$$T_{2N} = \begin{bmatrix} & C_N^{IV} \\ C_N^{IV} & \end{bmatrix} = \begin{bmatrix} I_N & \\ -C_N^{IV} & I_N \end{bmatrix} \begin{bmatrix} -I_N & C_N^{IV} \\ & I_N \end{bmatrix} \begin{bmatrix} I_N & \\ C_N^{IV} & I_N \end{bmatrix} \tag{10}$$

where I_N is the $N \times N$ identity matrix.

Equation (10) can be easily verified using the DCT-IV property in (3). Using (10), Equation (8) can be expressed as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} I_N & \\ -C_N^{IV} & I_N \end{bmatrix} \begin{bmatrix} -I_N & C_N^{IV} \\ & I_N \end{bmatrix} \begin{bmatrix} I_N & \\ C_N^{IV} & I_N \end{bmatrix} \begin{bmatrix} x_2 \\ x_1 \end{bmatrix} \qquad (11)$$

From (11), the following integer DCT-IV algorithms that simultaneously compute two integer DCT-IVs is derived.

The time to frequency domain integer transform is determined by the following:

Step 1) Compute

$$z = \lfloor C_N^{IV} x_2 \rfloor + x_1 \qquad (12a)$$

Step 2) Compute

$$y_1 = \lfloor C_N^{IV} z \rfloor - x_2 \qquad (12b)$$

Step 3) Compute

$$y_2 = -\lfloor C_N^{IV} y_1 \rfloor + z \qquad (12c)$$

where $\lfloor * \rfloor$ denotes rounding operation. Figure 2 illustrates the method of transforming a digital signal from the time domain to the frequency domain using DCT-IV as the transformation function. x_1 *and* x_2 are two blocks of the input digital signal, z is an intermediate signal, and y_1 and y_2 are corresponding blocks of the output signal.

The frequency to time domain integer transform is determined by the following:

Step 1) Compute

$$z = \lfloor C_N^{IV} y_1 \rfloor + y_2 \tag{13a}$$

Step 2) Compute

$$x_2 = \lfloor C_N^{IV} z \rfloor - y_1 \tag{13b}$$

Step 3) Compute

$$x_1 = -\lfloor C_N^{IV} x_2 \rfloor + z \tag{13c}$$

Figure 3 illustrates the method of transforming a digital signal from the frequency domain to the time domain using DCT-IV as the transformation function.

Conclusion of the above example

Equation (12) and (13) show that to compute two $N \times N$ integer DCT-IVs, three $N \times N$ DCT-IVs, three $N \times 1$ roundings, and three $N \times 1$ additions are needed. Therefore, for one $N \times N$ integer DCT-IV, the average is:

$$RC(N) = 1.5N \tag{14}$$

$$AC(N) = 1.5AC(C_N^{IV}) + 1.5N \tag{15}$$

where $RC(\,)$ is the total rounding number, and $AC(\,)$ is the total number of arithmetic operations. Compared to the directly converted integer DCT-IV algorithms, the proposed integer DCT-IV algorithm reduces RC from level $N \log_2 N$ to N. This is the result of doing rounding after the DCT-IV transform instead of in the DCT-IV transform.

As indicated by (15), the arithmetic complexity of the proposed integer DCT-IV algorithm is about 50 percent more than that of a DCT-IV algorithm. However, if *RC* is also considered, the combined complexity (*AC*+*RC*) of the proposed algorithm does not much exceed that of the directly converted integer algorithms. Exact analysis of the algorithm complexity depends on the DCT-IV algorithm used.

As shown in Figure 1 and 2, the proposed IntDCT-IV algorithm is simple and modular in structure. It can use any existing DCT-IV algorithms in its DCT-IV computation block. The proposed algorithm is suitable for applications that require IntMDCT, e.g. in the MPEG-4 audio extension 3 reference model 0.

The proposed algorithm is suitable for both mono and stereo applications. In mono applications, two consecutive blocks of samples are grouped and processed together. This introduces signal delay of one block length when compared to single-block processing. However, in stereo applications, this extra block delay can be prevented, if simultaneous sample blocks from the left and the right channel are grouped and processed together.

In this invention, a method for realizing reversible transformation function, for example for integer type-IV DCT transformation function, is proposed. This method requires significantly reduced number of roundings for every block of *N* input samples. As a result, the approximation error is greatly reduced. The method according to the invention is low in computational complexity and modular in structure.

Reference

[1] "Coding of Moving Pictures and Audio: Workplan for Evaluation of Integer MDCT for FGS to Lossless Experimentation Framework" *ISO/IEC JTC 1/SC 29/WG 11 N5578*, Pattaya, Thailand, Mar. 2003

[2] R. Geiger, T. Sporer, J. Koller, K. Brandenburg, "Audio Coding based on Integer Transforms" *AES 111th Convention*, New York, USA, Sept. 2001

[3] Z. Wang, "Fast Algorithms for the Discrete W Transform and for the Discrete Fourier Transform" *IEEE Trans. Acoustics, Speech, and Signal Processing*, vol. ASSP-32, No. 4, pp. 803-816, Aug. 1984

[4] Z. Wang, "On Computing the Discrete Fourier and Cosine Transforms" *IEEE Trans. Acoustics, Speech, and Signal Processing*, vol. ASSP-33, No. 4, pp. 1341-1344, Oct. 1985

What is claimed:

1. A method for transforming a digital signal from the time domain into the frequency domain using a transformation function comprising a transformation matrix, the digital signal is divided into a plurality of blocks, each block comprising a predefined number of data symbols, the method comprising:

- transforming the two sub-blocks by a transforming element, the transforming element comprises a plurality of lifting stages, wherein the two sub-blocks are received by a first lifting stage of the plurality of lifting stages as first and second input signals, and wherein each lifting stage comprises a transformation path, wherein the first input signal received by the lifting stage is processed by a domain transformer and a rounding unit, and is subsequently summed with the second input signal in a summation unit to result in an output signal; and wherein each subsequent lifting stage receives the output signal of the previous lifting stage as the first input signal, and the first input signal of the previous lifting stage as the second input signal, to generate the corresponding output signal of the subsequent stage.

2. The method of claim 1, wherein the transformation function is a DCT-I transformation function, DCT-IV transformation function, DST-I transformation function, DST-IV transformation function, FFT-I transformation function, FFT-IV transformation function, DWT I transformation function or DWT IV transformation function.

3. The method of claim 1 or 2, wherein each lifting stage corresponds to a lifting matrix, the lifting matrix comprises four sub-matrices with two permutation matrices as two of the sub-matrices in one diagonal, and with the transformation matrix and a zero as the other two of the sub-matrices in the other diagonal.

4. The method of claim 3, wherein the permutation matrices in each lifting matrix are identity matrices.

5. The method of any one of claims 1 to 4, wherein three lifting stages are used in the lifting ladder model for transforming the two blocks of the digital signal.

6. A method for reversibly transforming a digital signal from the time domain into the frequency domain, the digital signal is divided into a plurality of blocks, each block comprising a predefined number of data symbols, the method, for a first and second block of the digital signals, comprising

- generating an intermediate signal by
  - -transforming the second block of the digital signal to a transformed second signal using a transformation function;
  - - rounding the transformed second signal to a rounded second signal such that the value represented by the transformed second signal is rounded to an integer value; and
  - - adding the first block of the digital signal to the rounded second signal,
- generating a first output signal by
  - - transforming the intermediate signal to a transformed intermediate signal using the transformation function;
  - - rounding the transformed intermediate signal to a rounded intermediate signal, such that the value represented by the transformed intermediate signal is rounded to an integer value; and
  - - subtracting the second block of the digital signal from the rounded intermediate signal,
- generating a second output signal by
  - - transforming the first output signal to a transformed output signal using the transformation matrix;
  - - rounding the transformed output signal to a rounded output signal, such that the value represented by the transformed output signal is rounded to an integer value; and
  - - subtracting the rounded output signal from the intermediate signal,

wherein the first and second output signals are the transformed first and second block of the digital signal, respectively.

7. A device for transforming a digital signal from the time domain into the frequency domain using a transformation function comprising a transformation matrix, the digital signal is divided into a plurality of blocks, each block comprising a predefined number of data symbols, the device comprising:

- a transformation unit for transforming the two sub-blocks by a transforming element, the transforming element comprises a plurality of lifting stages, wherein the two sub-blocks are received by a first lifting stage of the plurality of lifting stages as first and second input signals, and wherein each lifting stage comprises a transformation path, wherein the first input signal received by the lifting stage is processed by a domain transformer and a rounding unit, and is subsequently summed with the second input signal in a summation unit to result in an output signal; and wherein each subsequent lifting stage receives the output signal of the previous lifting stage as the first input signal, and the first input signal of the previous lifting stage as the second input signal, to generate the corresponding output signal of the subsequent stage.

8. A computer readable medium, having a program recorded thereon, wherein the program is to make the computer execute a procedure transforming a digital signal from the time domain into the frequency domain using a transformation function comprising a transformation matrix, the digital signal is divided into a plurality of blocks, each block comprising a predefined number of data symbols, the method comprising:

- transforming the two sub-blocks by a transforming element, the transforming element comprises a plurality of lifting stages, wherein the two sub-blocks are received by a first lifting stage of the plurality of lifting stages as first and second input signals, and wherein each lifting stage comprises a transformation path, wherein the first input signal received by the lifting stage is processed by a domain transformer and a rounding unit, and is subsequently summed with the second input signal in a summation unit to result in an

output signal; and wherein each subsequent lifting stage receives the output signal of the previous lifting stage as the first input signal, and the first input signal of the previous lifting stage as the second input signal, to generate the corresponding output signal of the subsequent stage.

9. A computer program element which is to make the computer execute a procedure for transforming a digital signal from the time domain into the frequency domain using a transformation function comprising a transformation matrix, the digital signal is divided into a plurality of blocks, each block comprising a predefined number of data symbols, the method comprising:

- transforming the two sub-blocks by a transforming element, the transforming element comprises a plurality of lifting stages, wherein the two sub-blocks are received by a first lifting stage of the plurality of lifting stages as first and second input signals, and wherein each lifting stage comprises a transformation path, wherein the first input signal received by the lifting stage is processed by a domain transformer and a rounding unit, and is subsequently summed with the second input signal in a summation unit to result in an output signal; and wherein each subsequent lifting stage receives the output signal of the previous lifting stage as the first input signal, and the first input signal of the previous lifting stage as the second input signal, to generate the corresponding output signal of the subsequent stage.

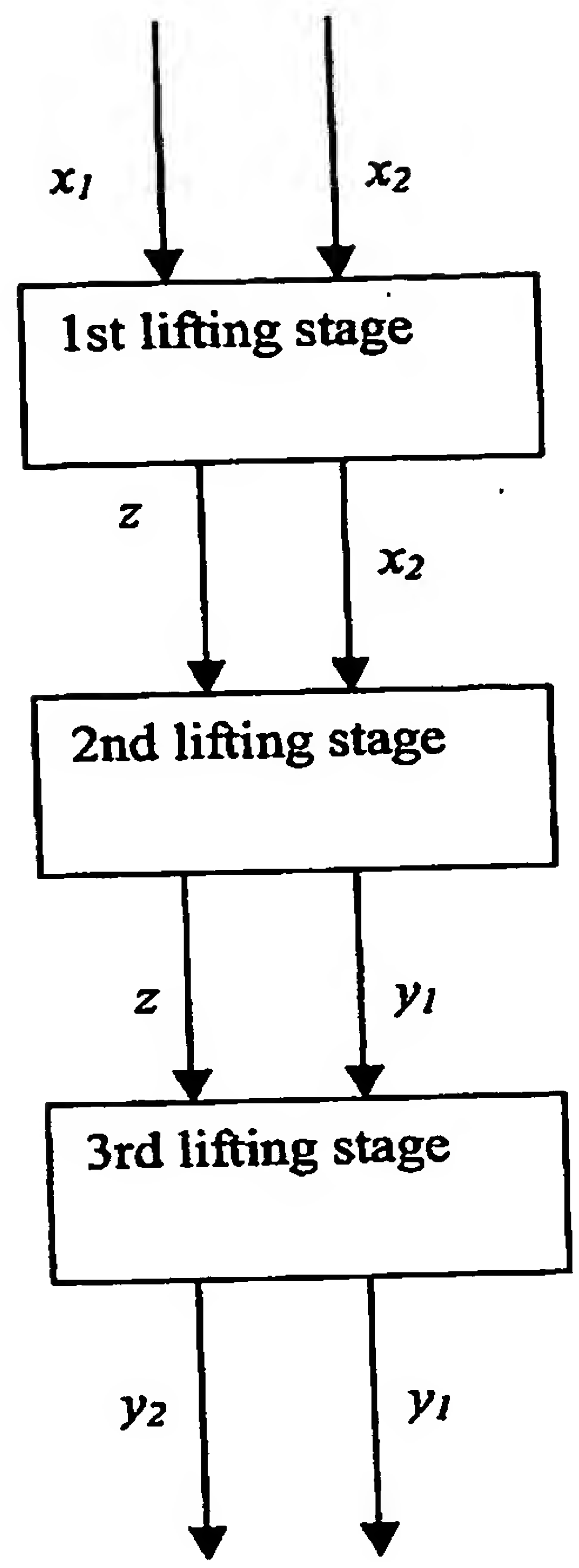
x_1
x_2
1st lifting stage
z
x_2
2nd lifting stage
z
y_1
3rd lifting stage
y_2
y_1

Figure 1

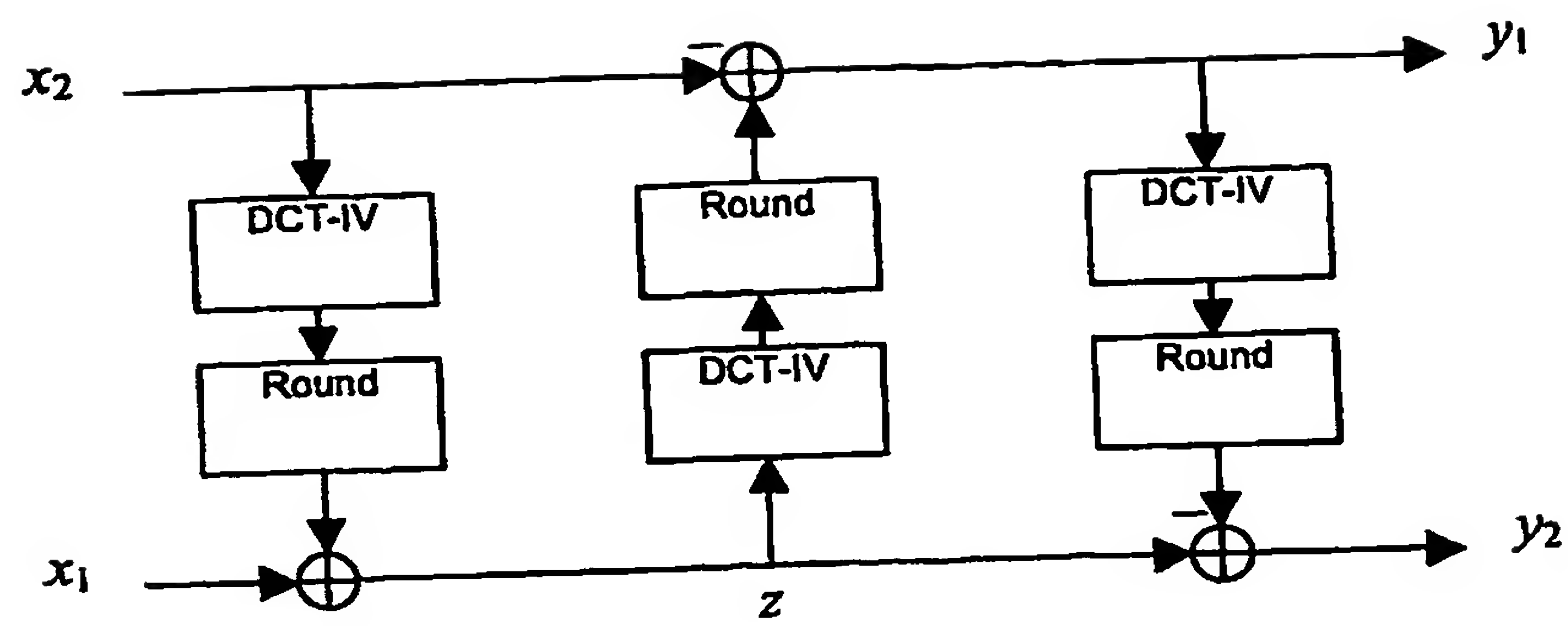

Figure 2. Forward IntDCT-IV flowchart

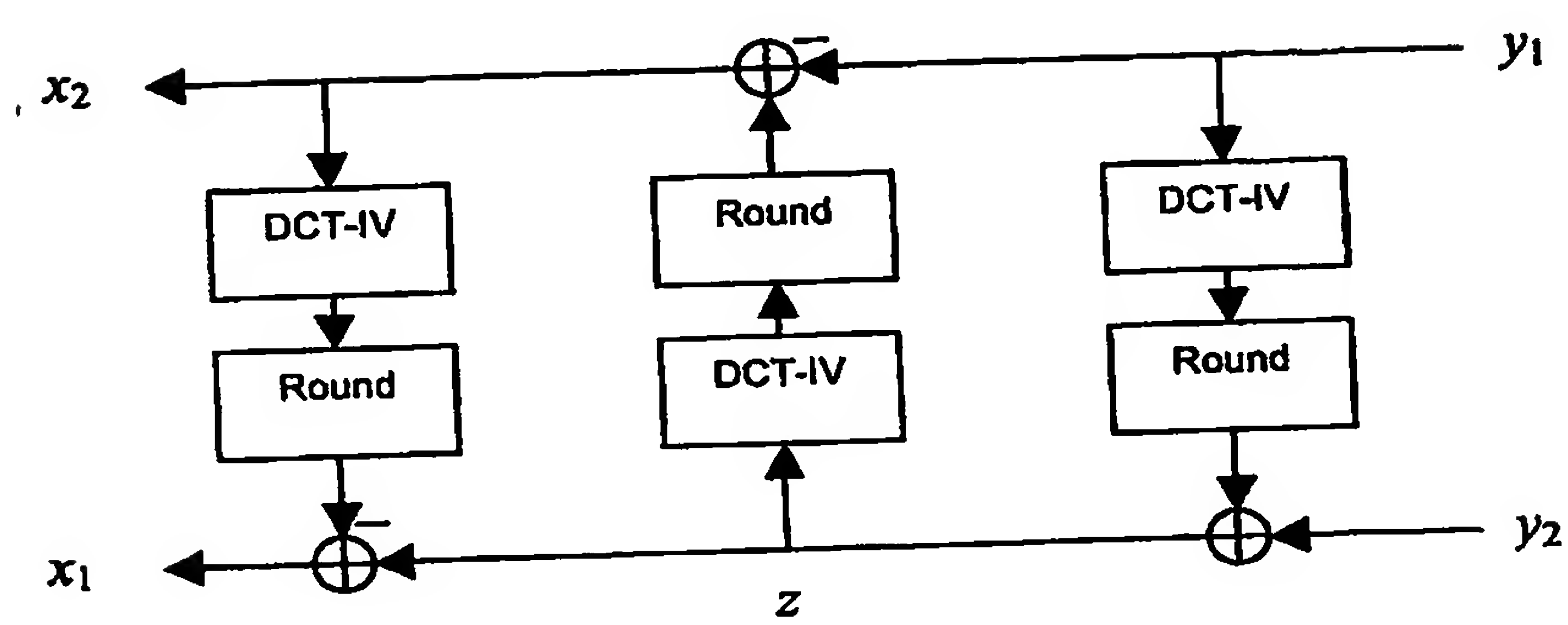

Figure 3. Inverse IntDCT-IV flowchart